Approaching Industrial Symbiosis through Agent-Based Modeling and System Dynamics

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Abstract Sustainable industrial systems are complex, since they exhibit both detail and dynamic complexity. Only an integrated approach is able to provide a realistic view of such complex systems providing a useful insight into their behavior. In this paper, a hybrid approach based on Agent Based Modeling (ABM) and System Dynamics (SD) is presented in order to improve modeling insight of an industrial symbiosis (IS) context. Hybrid approaches have gained prominence overpassing limitations of traditional methodologies and tools, as well as computational advances, that permit better modeling and analysis of complex systems with a particular focus on sustainability topics exploiting the strengths of both ABM and SD models, while minimizing the drawbacks. Therefore, to provide a methodological proof, an application of the proposed hybrid approach to an industrial symbiosis relevant case is presented and discussed. The methodological approach adopted in this research can be used to investigate a variety of industrial symbiosis cases providing insights usually not achievable with standard techniques and tools.

Keywords: Hybrid approach, Agent based modeling, System dynamics, Industrial symbiosis.

1 Introduction

In the last few years, sustainability has caused much interest and has driven companies to reengineering their processes and products with the aim of achieving greater efficiency from materials, resources and then obtaining an economic value from waste. This change brings about a better awareness of the production cycle, and material consumptions by reducing resources (energy and water), emissions and the production of products, all of which are sustainable in the whole life cycle.

An additional step in the sustainable development is represented by the so-called Industrial Symbiosis (IS), this involves the collaboration between two or more industries, which with specific agreements support the exchange of waste and by-products to be used as raw materials for production processes without resorting to the use of new raw materials. Chertow defines IS as “the collaboration of individual entities to a common approach which leads to a competitive advantage that involves exchange of materials, energy, water and by-products” (Chertow and Park, 2016).

In this paper, a hybrid approach based on Agent Based Modeling (ABM) and System dynamics (SD) is presented in order to improve modelling insight of an industrial symbiosis context with the aim of moving beyond the static representation of the environmental-economic variables and deal with the system’s dynamic complexity. Specifically, IS has been selected as a proof of concept for the proposed hybrid model. Indeed, there is a need for decision making tools that will be able to simulate the IS system’s response to different policies therefore allowing more informed decisions.

1.1 Agent-based Models and Sustainability

Agent-based Models (ABM) or multi-agent systems are a class of computational models designed to simulate action and interaction between autonomous agents. They can be both individual or collective entities, such as organizations, and have the aim of studying the effects at aggregate level. ABMs have gained prominence through new insights on the limitations of traditional assumptions and approaches, and improve computational advances have permitted better modeling and analysis of complex systems and particularly in the field of sustainability. ABMs in the industrial sustainability domain are emerging and various authors have identified the potential value and effectiveness, and advocated these approaches for their characteristics (Tonelli *et al.*, 2016). The key advantage is the ability to take into account heterogeneity and behavioural interactions, which can lead to emergent behaviour that would not be obvious or might be very difficult to foresee in an aggregate model as it could occur in the current manufacturing networks (Tonelli *et al.*, 2016).

1.2 System Dynamics and Sustainability

System dynamics (SD) is a methodology developed at the end of 1950s at the M.I.T. in Boston. Often human beings operate in systems characterized by high level of dynamic complexity; these systems could be connected to sustainability, physics, ecology, sociology and economy. SD is a representative method for measuring the long-term dynamics of the complex system, which fits for measuring the dynamics of sustainability. It is a simulation method to identify behavioural changes according to the structural characteristics of a system on the basis of the causal relationships among system factors (Lee *et al.*, 2012). The inherent flexibility and transparency is particularly helpful for the development of simulation models for complex sustainability systems with subjective variables and parameters. Therefore, this method can consistently be used to understand sustainability discussions (Golroudbary and Zahraee, 2015).

1.3 Hybrid approach and Sustainability

ABM and SD are among the most important simulation methods available; both of these approaches are used to study the leverage points of complex systems. Advantages and limitations of individual methods were the motive for the emergence of integrated simulation approach. Sustainable systems are complex; they exhibit both detail and dynamic complexity, in fact they represent a form of Complex Adaptive Systems (CAS) because they involve multiple sectors and agents displaying non-linear and non-rational interacting behaviours characterized by feedbacks and time lags. Therefore, we claim that a hybrid SD-ABM approach may potentially better address such issues in a more informative and effective way because they exploit the strengths of both models, while minimizing the drawbacks, providing a more realistic view of such complex systems (Abdelghany and Eltawil, 2017). Lättilä *et all.*, argue that by using both the methods, they will improve the quality of the model and give more in-sights, but at the same time they highlight the need for further researches regarding the actual simulation models (Lättilä, Hilletofth and Lin, 2010). SD and ABM are developed around the real characteristics of the phenomenon they aim at reproducing and simulating, limiting the use of assumptions. In this way, they provide a useful platform to model non-linear phenomena, in particular, they are able to: i) show the impact of indirect effects on the agents and components of the model; ii) shape relations according to their governing feedback loops; iii) internalize an agents' behaviour (ABM) or system relations (SD) linked to externalities of specific actors and situations (Monasterolo *et al.*, 2014). Thanks to these desirable characteristics, these modeling tools are able to shed greater light on the world we are living in, characterized by time lag between agents' decisions (governments, households, industries) and non-rational actors. Moreover, providing a closer representation of reality, they are also able to show the "unintended effects" of the introduction of new policy measures, such as the rebound effect. Finally, it is possible to say that SD and ABM complement each other.

The purpose of this paper is to develop a hybrid model for IS and the main objectives are:

- Assess sustainability in the IS network;

- Simulate the IS network in order to better understand and analyze critical problems;
- Analyze how resources' consumption changes with respect to the symbiosis.

The paper is organized as follows. Section 2 introduces the Research methodology adopted for this paper. Section 3 presents the hybrid model, the practical application and the simulation scenarios. Section 4 gives the Results and discussions, and finally Section 5 provides conclusions.

2 Methodological approach

2.1 Introduction

A hybrid system of ABM and SD has been proposed in order to address the unique characteristics of the IS problem such as: (i) nonlinear properties, which would not allow us to use classic econometric models, (ii) positive and negative feedback, which influence its behaviour. These behaviours can be fully understood in the interactions of the models. In particular, with SD-ABM hybrid approach we can model a component for SD and/or ABM, but it is only run with the most effective one at a given time. The hybrid modeling and simulation approach are suitable to evaluate the system outputs in both macroscopic and microscopic points of view (Wang and Moon, 2013). IS presumes that industries collaborate intentionally and organize themselves in order to reach not only a better use of materials, but also a partnership that permits them to share strategies and objectives. In this direction, the adoption of the hybrid approach for IS allows examining different strategies, creating a dynamic environment for agents, which can actively behave in the system and interact with each other. In the work discussed here, system dynamics have been selected for considering flows and feedback dynamics from an aggregated viewpoint. SD reveals the trend and system-level behaviour explicitly and intuitively. On the other hand ABMs have been selected because they assume no fixed system structure and the overall system behaviour emerges from individual agent rules, thus making it a bottom-up modelling approach. The IS system has been simulated by the Anylogic tool, which provides both the agents and the SD model. The challenge is to determine:

1. Which are the individual behavioural aspects that may favour industrial symbiosis?
2. What are the overall benefits associated with the entire industrial network?

2.2 *Case description*

IS has been selected as a proof of concept for the proposed hybrid model. The scope of the model is the creation of an eco-industrial development plan by incorporating the basic ideas of industrial symbiosis, industrial ecology and eco-industrial parks. The model considers an industrial network made up of 4 firms. Each firm produces a single main product sold on the final market. The production process requires a single input, purchased from the external supply market, and generates a single waste product, which is destined for landfill. Each firm gets revenues from selling its main product, while production costs are in the form of purchasing and waste disposal. We considered 4 industries: a manufacturer of mechanical components (MC), a steel plant (SP), a cement plant (CP) and a paper factory (PF). Table 1 shows Input/output materials for each industry; while Figure 1 depicts the available links between the 4 companies. We assume that each firm can send and receive waste from any firm. Each firm within the industrial network is modeled as an agent, who decides whether or not to establish a symbiotic relationship with another firm belonging to the other industries.

Table 1 Input/output materials for each industry

Industry	Input	Output	Waste
Mechanical components	Cast iron	Pulley	Cast iron
Steel plant	Carbon/cast iron	Steel	Slag steel
Cement plant	Sand/mixed metal slag	Cement	Waste water
Paper factory	Wood pulp	Paper	Paper mill waste sludge

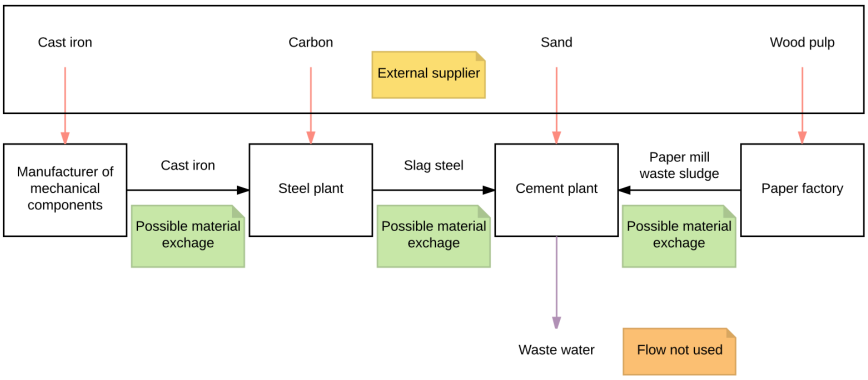

Figure 1 Available links between the four companies

2.3 Model development: SD + ABM

In this section the SD and ABM models have been developed and described. The hybrid model was developed in AnyLogic simulation software. In general, SD modeling uses stocks and flows. Stock is the state of a system and describes its current status. The flow affects the stock and interlinks it within its system. When the dynamic model is properly developed, the quantitative representation can be simulated. The dynamic behaviour of the system can be explained by a set of mathematical equations, which are described next. The dynamic behaviours of stock (such as “Raw material inventory”, “Service inventory”, “Final products inventory” and “Waste inventory”) are given by a time integral of the net inflows minus the net outflows. Due to the high number of variables, the specific mathematical formulation and process model description has been illustrated for one of these models, the others have been reported in the Appendix section (Figure 11).

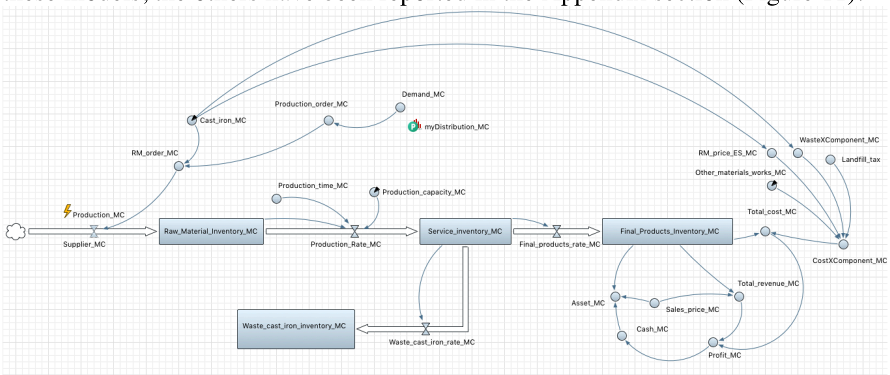

Figure 2 Hybrid model of the Manufacturer of mechanical components

Figure 2 shows the SD-ABM model of the manufacturer of mechanical components, it produces pulleys starting from a customer order. This process has been managed through the variable demand, which is modeled as a random walk. In fact, it consists of a succession of demands, and each demand takes in consideration the previous one. After an order is received, a production order is generated and at the same time the raw material order is created. The raw material order is linked to the external supplier, which in this specific industry provides cast iron. The raw material flow provided by the external supplier is controlled by an event called “Production MC”. This event allows the material transfer only if the raw material’s level is below a specific value. This event stops warehouses filling up in an uncontrolled way. At the beginning of the simulation, it has been assumed that there are no symbioses between firms, and then only external suppliers provide raw materials. After the procurement phase, raw materials are stored in the raw material inventory in which they wait to be worked. The production phase allows transforming raw materials into final products; this step is done through a constant monitoring of the production capacity, which varies for each factory. Table 3 shows production time and production capacity for each firm.

Table 3 Production times and production capacities of each firm

	Production Time [Week]	Production capacity [Ton]
Mechanical components	3	4000
Steel plant	3	35
Cement plant	1	10500
Paper factory	1	1200

During the production process, each firm generates wastes: 5% for Mechanical components, 9% for Steel plant, 5% for Cement plant, 8% for Paper factory.

Finally, for each firm an economical analysis is provided. In fact, each firm obtains revenues from selling its main product (it has been assumed that all final products are sold), while production costs are in the form of purchasing and waste disposal costs. Figure 3 depicts the detail concerning revenue, cost and profit of each firm of the hybrid model. If there is no link between factories, total costs are the sum of purchasing costs which depends on the raw materials price imposed by the external supplier, waste disposal costs, which depends on the landfill tax imposed by government, and other generic materials and works costs, which take into account costs of other raw materials and works with the scope of providing reasonable profit results. These considerations about other generic materials are also made for the material flow in order to respect the mass balance. Revenues are calculated as the product of final goods and the sale price. Finally, there are two last variables, which are Cash and Assets; the first one shows the current level of cash in terms of income and outflow money; while assets analyse the value of the company in terms of profit, cash and value of warehouses.

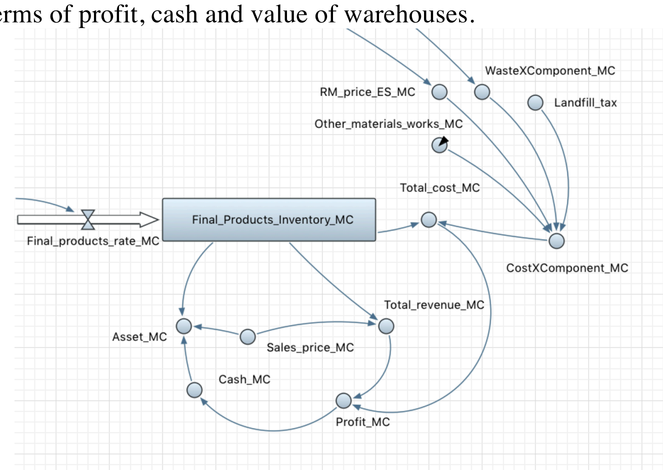

Figure 3 Revenue, cost and profit detail of the hybrid model

On the contrary, if there are symbiosis linkages between firms, total costs are in the sum of purchasing cost, which now depend on the cost policy adopted by the symbiotic firm, and the other generic material and works. Obviously, waste disposal costs are not mentioned anymore. At this point it is important to underline that in some cases waste effectively becomes “a credit” as iron cast maintains a value, but in other cases waste remains a cost, as the company must pay the other firm for taking its waste away. The firm at the most must pay the landfill tax. In this case revenue is in terms of sold final product and profit derived by the symbiosis.

Finally the whole mathematical formulation is:

$$Production\ rate = min(Production\_capacity\_MC, Raw\_Material\_Inventory\_MC)/ Production\_time\_MC \ (1.1)$$

$$Waste\ rate \ = \ 0.05 * Service\_inventory_{MC} \ (1.2)$$

$$Final\ produc\ rate \ = \ 0.95 * Service\_inventory_{MC} \ (1.3)$$

$$CostXComponent_{MC} \ = \ Landfill\_tax * WasteXComponent_{MC} + RM\_price\_ES_{MC} + Other\_materials\_works_{MC} (1.4)$$

$$Total\ cost \ = \ (CostXComponent_{MC} * Final\_Products\_Inventory_{MC}) \ (1.5)$$

$$Total\ revenue \ = \ (Final\_Products\_Inventory_{MC} * Sales\_price_{MC} \ (1.6)$$

$$Profit \ = \ Total\ revenue - Total\ cost \ (1.7)$$

$$Cash \ = \ Initial\ value + Profit \ (1.8)$$

On the other hand the ABM model is described below; the model consists of core entities called agents and links. Each firm within the industrial network is modeled as an agent, who decides whether or not to establish a symbiotic relationship with another firm belonging to the feasible industry. Therefore, four agents with the same name of the aforementioned firms compose the model, and it has been assumed that each agent has a population of 100 firms. A symbiotic function is defined, which measures the willingness of firm “i” to exchange wastes with firm “j” and vice versa. Shown below is the symbiotic function calculated considering that firm “j” is selling its waste to firm “i”. At this point, it is important to underline that, the symbiotic function also takes into account the pre-processing cost, in order to make the external raw material supplier price competitive with the waste price.

$$Symbiotic\ function\ (\mathrm{i} \rightarrow \mathrm{j}\ ) = Money\ from\ (j \rightarrow i) - Preprocessing\ cost(i) > -External\ supplier\ raw\ material\ price \ (1.9)$$

$$Symbiotic\ function\ (j \rightarrow i) = Money\ from\ (j \rightarrow i) \leq Landfill\ tax \quad (1.10)$$

The abovementioned symbiotic function will be calculated in the state chart of each agent, but the required data is captured from the SD model. The state chart of each agent is composed of two states “No symbiosis” and “Symbiosis”. To move from one state to another, it is necessary that the symbiotic condition is verified. Thanks to the agents network, another important variable has been introduced, the Green Image Factor (GIF). In fact, IS has a positive impact on the company image. Therefore interestingly as green product, IS can result in two benefits: i) product price could increase, ii) raise in number of sales. Also in this case, GIF is calculated thanks to the introduction of an event “Calculate GIF”, which takes data from the SD model.

Furthermore, the ABM model allows implementing another important aspects of the firms’ life cycle: birth and death. In fact, accordingly with the profit generated by firms that is visible in the SD model, new firms/agents are pushed to enter into the market while other ones must leave the market caused by high costs.

To conclude, as previously discussed, the SD model considers flows and feedback dynamics from an aggregated viewpoint, while the ABM model describes in a clearer manner the behaviour within the company.

3 Results and Discussion

In this section the results obtained from the simulation runs are reported and discussed following the two research questions. In the following table, simulation parameters are reported.

Table 4 Simulation’s parameters

	Simulation parameters
Model unit time	Week
Landfill tax	18€/ton
Input purchasing cost MC	1800 €/ton
Sales price MC	208 €/Pulley
Input purchasing cost SP	250 €/ton
Sales price SP	1200 €/ton
Input purchasing cost CP	20€/ton
Sales price CP	120 €/ton
Waste cast iron price	140 €/ton
Sales price PF	2000 €/ton
Input purchasing cost PF	85 €/ton

3.1 Which are the individual behavioural aspects that may favour industrial symbiosis?

Figure 4 shows simulation results for the raw material scenario. We find that there is a correspondence between the raw material demand, price and the number of IS. In fact, if external supplier's demand decreases because of the increasing number of IS, there is a resulting decrease in the raw material price. This means that external suppliers in order to be competitive with the waste price need to reduce their price. The behaviour of the market in the long term results in a fluctuations between raw material suppliers' price and waste product price. Therefore, IS will reach a point where it becomes unattractive for companies. There is a delicate balance between the positive effects of GIF and the negative effects due to long term fluctuations in prices, which can bring about system failure.

Another interesting behavioural aspect is linked to pre-processing cost (Figure 5). When the number of IS is low, pre-processing cost are high; on the contrary, when the number of IS increases, there is a resulting decrease in the pre-processing cost. This behavioural aspect could become clearer considering that at the beginning of the simulation the number of IS is low, so there are few firms that are able to provide pre-processing production, on the contrary when the IS raises, also the pre-processing market becames more competitive and firms have learned how do it better.

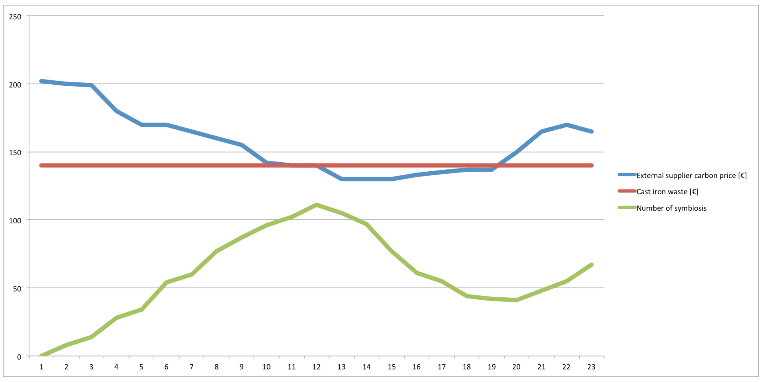

Figure 4 Raw material's price behavior with respect to the number of IS

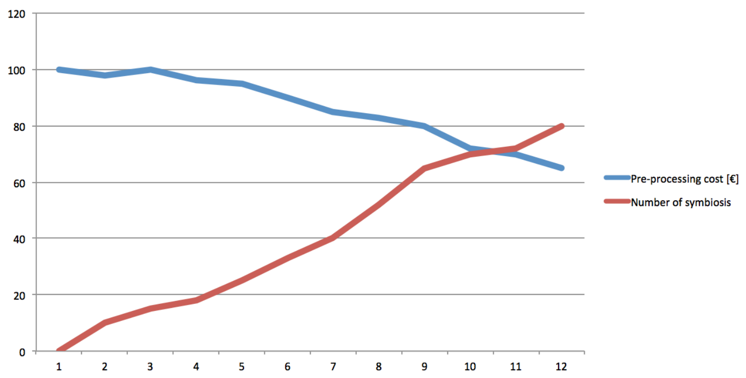

Figure 5 Pre-processing's cost behavior with respect to the number of IS

3.2 What are the overall benefits associated with the entire industrial network?

Finally we can report a comparison between the scenario with no symbiosis and the symbiotic one (Figure 6-9). We can notice that the difference between the two profits is small at the beginning of the IS, and then increases over time. This aspect could be caused by i) complex interaction of technologies and process, ii) technical and regulatory barriers, which can be overcame over time.

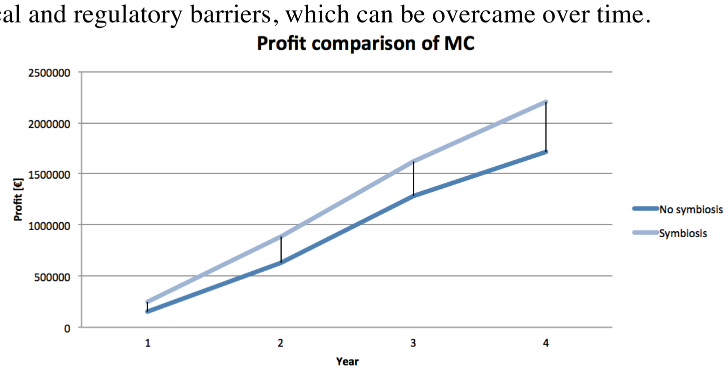

Figure 6 Profit comparisons for MC

4 Conclusions and Future Developments

At the current state of the model's development, the results are promising, but they still need revision. The model still needs some improvements as well as an enhanced validation in order to deliver more realistic results. However, its design is seen as an approach to modeling multi-agent network systems that may serve as the basis for the development and sustainability of industrial symbiosis.

One of the limitations of the present work is that transportation costs are not addressed. Even though, the current model is a good foundation for further iterations, and it could be a good starting point in order to better investigate the hybrid simulation field.

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Appendix

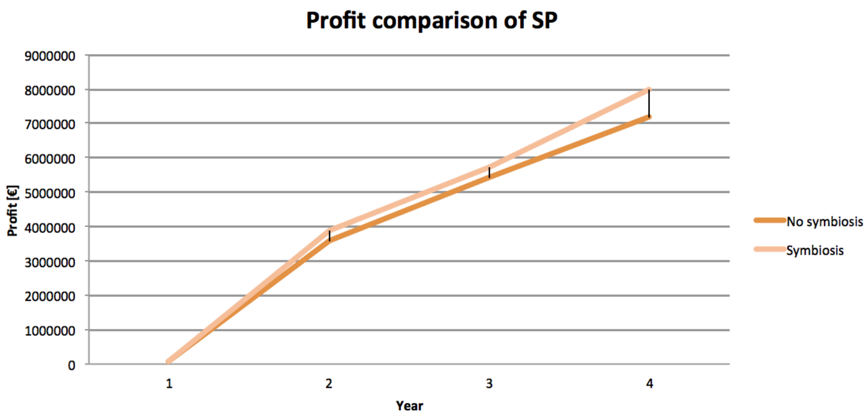

Figure 7 Profit comparisons for SP

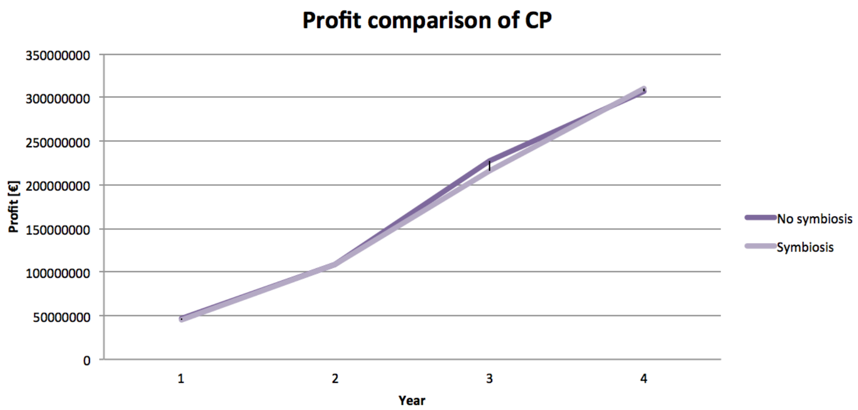

Figure 8 Profit comparisons for CP

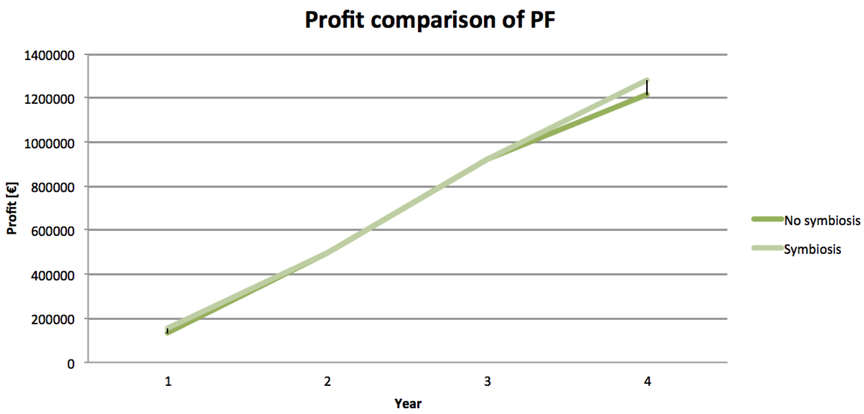

Figure 9 Profit comparisons for PF

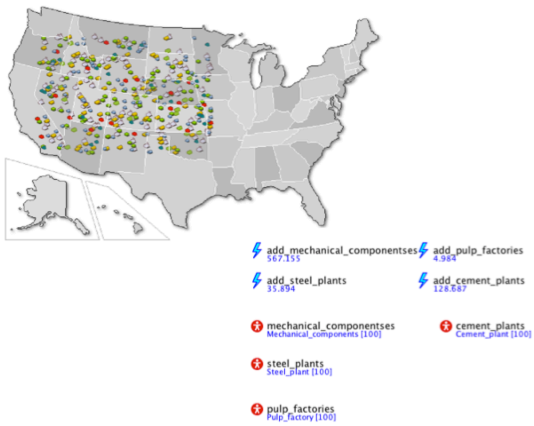

Figure 10 Detail of the ABM-SD approach

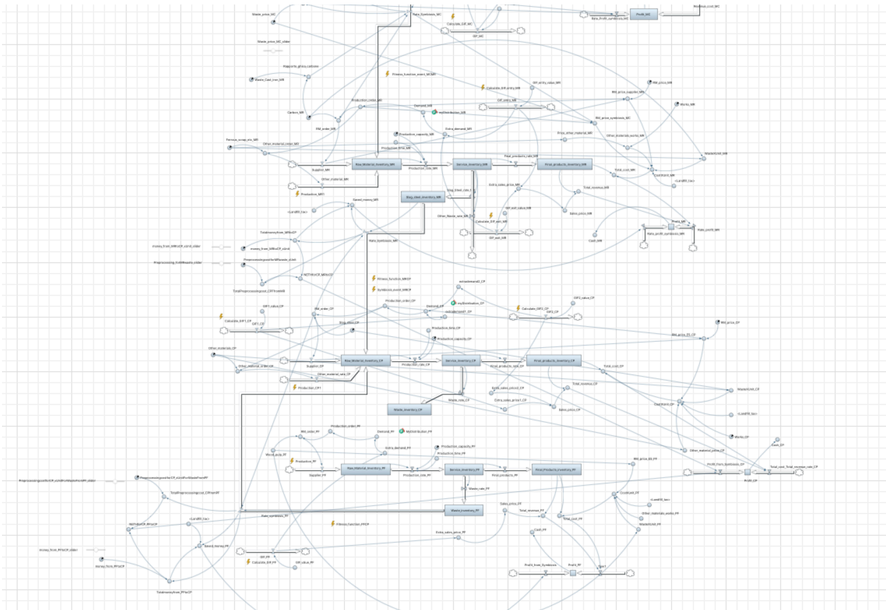

Figure 11 SP, CP, PF hybrid approach